Thunder-induced ground motions: 2. Site characterization

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[1] Thunder-induced ground motion, near-surface refraction, and Rayleigh wave dispersion measurements were used to constrain near-surface velocity structure at an unconsolidated sediment site. We employed near-surface seismic refraction measurements to first define ranges for site structure parameters. Air-coupled and hammer-generated Rayleigh wave dispersion curves were used to further constrain the site structure by a grid search technique. The acoustic-to-seismic coupling is modeled as an incident plane $P$ wave in a fluid half-space impinging into a solid layered half-space. We found that the infrasound-induced ground motions constrained substrate velocities and the average thickness and velocities of the near-surface layer. The addition of higher-frequency near-surface Rayleigh waves produced tighter constraints on the near-surface velocities. This suggests that natural or controlled airborne pressure sources can be used to investigate the near-surface site structures for earthquake shaking hazard studies.


1. Introduction

[2] Lin and Langston [2007] showed that the acoustic shockwave of thunder induces measurable ground motions that can be used as a natural seismic source to study near-surface site structure and site resonance effects. Indeed, significant thunder-induced ground reverberations at their site in western Tennessee require low near-surface $P$ and $S$ wave velocities so that all $P$ wave and $P$-to-$S$ reverberations are locked in the near-surface layer to form an air-coupled Rayleigh wave for horizontally propagating acoustic waves [Lin and Langston, 2007]. Lin and Langston [2009] (hereafter referred as paper 1) examined 19 thunder events to investigate the acoustic/seismic wavefield in detail and to establish a systematic relation between the incident acoustic source wave and induced ground motions. Eighteen out of the nineteen thunder events studied in paper 1 induced by horizontally propagating acoustic waves showed consistent clear ground motion reverberations at a frequency between 4 and 7 Hz. Particle motion analysis of these ground reverberations in paper 1 showed that these are air-coupled Rayleigh waves. We also developed a source equalization procedure for acoustic/seismic deconvolution similar to that for obtaining teleseismic receiver functions [Clayton and Wiggins, 1976; Langston, 1979] to obtain an estimate of the impulse response of the ground to incident acoustic pressure. For 18 thunder events showing an extensive reverberation series, the dominant frequencies of the acoustic-to-seismic ground motion transfer function and incident slownesses (inverse phase velocity) inferred from the seismic ground velocity have a clear systematic relation (Figure 1; modified from Figure 13 in paper 1). Recognizing that these thunder-induced ground reverberations are air-coupled Rayleigh waves, the phase velocity of these ground reverberations and the dominant frequency of the acoustic-to-seismic ground motion transfer function might serve as part of the medium’s Rayleigh wave phase velocity dispersion relation.

[3] In this paper our main objective is to quantitatively constrain the near-surface array site structure by using the seismic observations of the thunder-induced ground motion with constraints afforded by near-surface body wave refraction and Rayleigh wave dispersion data. Our working hypothesis is that the thunder-induced ground motions can be used to quantitatively constrain the near-surface site structure. First, an Earth model for the array site will be inferred from standard near-surface refraction and surface wave dispersion techniques. High-frequency Rayleigh wave dispersion curves will be extracted from the same seismogram profiles used in the refraction analysis. Next, another Earth model will be obtained by modeling the air-coupled Rayleigh wave dispersion from the thunder-induced ground motions and the acoustic-to-seismic ground motion transfer functions. Finally, we will compare these two results to find the best, jointly constrained Earth model for the array site. The resulting simple Earth model is sufficient to explain the characteristics of the observed thunder-induced ground motions and the dispersion data. The low surface seismic velocities of the resulting Earth model have important implications on earthquake hazard studies [Borcherdt, 1970; Toro et al., 1992] since a low seismic velocity layer tends to amplify ground shaking level. Another motivation...
Figure 1. (a) Dominant frequency of the acoustic-to-vertical ground motion transfer function versus horizontal slowness (inverse phase velocity) inferred from the vertical ground motions of 18 thunder events showing long reverberation series (modified from Figure 13 in paper 1). The line indicates the linear regression fit and its error estimates. (b) Same as Figure 1a except converting horizontal slowness to the horizontal phase velocity commonly used in surface wave dispersion plots.

Figure 2. Examples of $P$ and $S$ wave source shot gathers used in the refraction analysis and the extraction of the Rayleigh wave ($P$ wave profile) dispersion curves plotted with picked direct and refracted waves. The interpreted ranges of the simple one layer over a half-space velocity models are shown in the legend and the thickness of the surface layer ranges between 8 and 12 m. Vertical ground motion is shown for the $P$ profile and horizontal motion perpendicular to the line shown for the $SH$ profile.
for this study is to gain better understanding of acoustically induced noise for shallow seismometers.

2. Near-Surface Velocity Structure From Small-Scale Refraction

Langston [2004] and Lin and Langston [2007] showed that seismic waves induced by atmospheric shock waves from bolide and thunder sources usually do not significantly interact with deeper structure greater than about 30 m. Velocity structure at the array site to a depth of tens of meters is of most interest to this study. A 24-channel linear refraction profile with 2-m receiver spacing and two 2-m off-end hammer shots were used to acquire the SH and P wave data. A total record length of 512 ms and a sampling rate of 0.25 ms were used in the recording scheme. The SH wave energy source consisted of a sledgehammer horizontally striking a wooden timber placed perpendicular to the geophone spread on the ground under truck wheels. The P wave energy source consisted of a steel plate on the ground struck vertically by a sledgehammer.

Figure 2 shows example shot gathers of the small-scale refraction data set plotted with the arrivals of direct and refracted waves and the interpreted ranges of Earth model parameters for a simple one layer over a half-space velocity model (Table 1). These ranges define the limits of the Earth model parameters later used in the hammer-generated Rayleigh wave dispersion analysis.

3. Hammer-Generated Rayleigh Wave Dispersion Analysis

We measured the hammer-generated high-frequency Rayleigh wave phase dispersion by band-pass filtering the vertical component shot gathers and then manually picking the troughs or peaks of the Rayleigh wave phase arrivals. We obtained the Rayleigh wave phase velocity and its corresponding error for one individual frequency range through a linear regression fit of the time-distance picks. The band-pass filter used consisted of a one-pass, two-pole Butterworth filter with corner frequencies at ±10% of the central frequency. The resulting dispersion curves for the first two Rayleigh modes are shown in Figure 3. Because the filtered vertical component shot gathers show strong surface wave component, and is a small amount of shot gather data (one profile line), we decided that the simple time domain picking method is sufficient enough to extract the dispersion curves for this one short, linear refraction profile. These dispersion curves were late confirmed with the frequency-wave number spectral method in Figure 8.

Figure 3. Hammer-generated Rayleigh wave dispersion curves for the first two modes obtained by manually picking the time domain Rayleigh wave phases on the band-pass-filtered P wave seismogram profiles.

Table 1. Earth Models From Refraction and Rayleigh Wave Dispersions

<table>
<thead>
<tr>
<th></th>
<th>P Wave Velocity (m/s)</th>
<th>S Wave Velocity (m/s)</th>
<th>Thickness (m)</th>
<th>Poisson’s Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Surface Layer</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Refraction</td>
<td>380–480</td>
<td>240–340</td>
<td>8–12</td>
<td></td>
</tr>
<tr>
<td>Air-coupled Rayleigh wave</td>
<td>385–425</td>
<td>265–300</td>
<td>11–11.5</td>
<td></td>
</tr>
<tr>
<td>Joint model</td>
<td>425–435</td>
<td>295–300</td>
<td>11</td>
<td>0.003–0.074</td>
</tr>
<tr>
<td><strong>Bottom Half-Space</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Refraction</td>
<td>850–1200</td>
<td>400–750</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Air-coupled Rayleigh wave</td>
<td>950–970</td>
<td>650–670</td>
<td></td>
<td>0.005–0.092</td>
</tr>
</tbody>
</table>

[7] The simple one layer over a half-space velocity model interpreted from refracted body waves (Figure 2 and Table 1) is further constrained by the Rayleigh wave dispersion. Rayleigh wave dispersion is typically considered as a good constraint on the S wave structure [Lai and Rix, 1998; Liu et al., 2000; Louie, 2001]. A systematic search of model parameters based on the ranges determined from the refraction results (Table 1) was performed to empirically examine the effects of seismic velocities and thicknesses on the measured Rayleigh wave phase velocity dispersion. As shown in Figure 4, the first higher-mode dispersion is more sensitive than the fundamental mode for depth of the layer interface (left bottom subplot) and the surface layer S wave velocity (right top subplot) suggesting the use of both fundamental and first higher-mode dispersion curves to constrain these model parameters. It can also be seen from Figure 4 that the lower half-space P and S wave velocities have insignificant effects on the variations of fundamental mode dispersion for frequencies higher than 12 Hz and the first higher mode for frequencies higher than 36 Hz (left middle and right bottom subplots). Because of this, it is more appropriate to use the hammer-generated Rayleigh wave dispersion curves to constrain the Vp and Vs of the surface layer and the surface layer thickness than the lower half-space Vp and Vs.

[8] We placed quantitative constraints on the first-layer Vp, Vs, and thickness by applying a grid search technique. Alternatively one can also conduct a simple inversion for these parameters. A grid search procedure is adopted here because the model space range predetermined by the refraction measurement is not that extensive, and therefore
can exhaustively sample the model space. We found the best fit parameters by minimizing the mean 1-norm phase velocity residual, $||\varepsilon||$, given by

$$||\varepsilon|| = \frac{1}{n} \sum_{i=1}^{n} |V_{\text{obs}}^i - V_{\text{calc}}^i|$$

where $n$ is the number of data points, which is equal to 26 for the hammer-generated Rayleigh wave observations. The use of the mean instead of sum of the 1-norm residual is for comparison purposes for grid search results calculated from the air-coupled and hammer-generated Rayleigh waves, respectively. Grid intervals of 5 m/s in seismic velocity and 0.5 m in thickness were used to cover the ranges of the model space and the $V_p/V_s$ ratios are restricted to having a positive Poisson’s ratio. The lower half-space $V_p$ and $V_s$ are set to 970 m/s and 650 m/s, respectively. The ranges of the model space and the values of the lower half-space $V_p$ and $V_s$ are

Figure 4. Rayleigh wave dispersion perturbation analysis. Various Earth model parameters based on the ranges of the refraction results are used to perform the forward computations. Perturbations of 5 m/s in seismic velocities and 0.5 m in thickness were used. The black lines with error bars show the hammer-generated Rayleigh wave dispersion curves in Figure 3.
Vs were chosen from the refraction analysis (Table 1). Figure 5 shows the resulting grid search for different layer thickness. We selected the ranges where the \(k/C_2\) have a difference to the minimum value of less than 5% to find our best fit parameters. The \(V_p\) and \(V_s\) of the surface layer can be further constrained by this analysis to ranges of 420 to 435 m/s and 290 to 295 m/s, respectively, and the layer thickness is between 10 and 11 m (Table 1).

4. Near-Surface Velocity Structure From Acoustic Transfer Functions

[9] The grid search method was also used on the thunder-induced air-coupled Rayleigh wave dispersion (Figure 1) to find the best fit Earth model (equation (1), \(n = 18\)). Note that the hammer-generated Rayleigh wave dispersion curves were not included in this grid search.

[10] The coupling between acoustic pressure and the ground is modeled as an incident plane \(P\) wave in a fluid half-space (atmosphere) impinging into a solid layered half-space (Earth model) [Ewing et al., 1957; Haskell, 1962; Langston, 2004]. We calculated the synthetic time domain transfer function from the synthetic pressure and vertical velocity seismogram through the deconvolution technique and found its dominant frequency. By varying the incident slowness, a theoretical air-coupled Rayleigh wave dispersion curve can be obtained. Particle motion plots for the radial-vertical plane and the radial-to-vertical ground motion time domain transfer function (see equation (12) in paper 1) were used to verify retrograde elliptical particle motion characteristic of Rayleigh wave propagation. Precisely speaking, the plane wave computation does not give a Rayleigh wave but a series of \(P\) and \(S\) wave reverberations. These are real, propagating \(P\) and \(S\) waves in the layer. The interference of these waves gives rise to a characteristic frequency that is a function of phase velocity.

[11] In order to compare the grid search results and the interpreted Earth model in Figure 5, we divided the five model parameters of the one-layer Earth model into two model space groups and performed a two-step grid search on the observed air-coupled Rayleigh wave dispersion. The observed air-coupled Rayleigh wave is at a frequency...
between 4 and 7 Hz. As shown in Figure 4, the \( V_p \) and \( V_s \) of the lower half-space, especially \( V_s \), have more effect upon the Rayleigh wave dispersion than the \( V_p \) and \( V_s \) of the surface layer and the surface layer thickness at a frequency between 4 and 7 Hz. The model space of the first step includes the \( V_p \) and \( V_s \) of the surface layer and the surface layer thickness, while the second step includes the \( V_p \) and \( V_s \) of the lower half-space. We again assumed the lower half-space \( V_p \) and \( V_s \) as 970 m/s and 650 m/s, respectively, and the same grid intervals to be consistent with the grid search on the hammer-generated Rayleigh wave dispersion curves (Figure 5).

[12] Figure 6 shows the first-step grid search results of the \( V_p \) and \( V_s \) of the surface layer and the surface layer thickness. In general, the \( V_p \) and \( V_s \) of the surface layer in the ranges of 385 to 425 m/s and 265 to 300 m/s, respectively, and the layer thickness between 11 and 11.5 m (Table 1) have minimum 1-norm residuals. These minimum 1-norm residuals are chosen to have residual values less than 6 m/s, which are consistent with the minimum ranges in Figure 5.

[13] By choosing the surface layer \( V_p \) and \( V_s \) as 425 m/s and 300 m/s, respectively, and the layer thickness as 11.5 m obtained from the first-step grid search results, we constructed various Earth models by varying the lower half-space \( V_p \) and \( V_s \) in the ranges given by the refraction analysis. Figure 7 shows that the lower half-space \( V_p \) and \( V_s \) of about 950 to 970 m/s and 650 to 670 m/s, respectively, have the minimum mean 1-norm residuals. The low-frequency coverage of the air-coupled Rayleigh wave dispersion from thunder, which samples deeper than the high-frequency hammer-generated Rayleigh wave dispersion, is found to be useful to constrain the lower half-space \( V_p \) and \( V_s \) (Figure 7). Yet this observation is specific to the site and to the relatively high-frequency hammer source with short offsets. Finally, the well-constrained Earth model initially interpreted from the refraction analysis is obtained and summarized in Table 1.

5. Discussion

[14] Although the extraction of the hammer-generated Rayleigh wave dispersion shown in Figure 3 is simple,
the resulting Earth model fits the observed dispersion curves well. In order to further check the credibility of the dispersion curves shown in Figure 3 obtained by using the time domain method, we employed the frequency-wave number spectral method [Zywicki, 1999; Hebeler, 2001] to transform the time domain data into the frequency-phase velocity domain and then extract the dispersion curves from the frequency-phase velocity image. The use of the frequency-wave number spectral method here is because this method is an inherent array-based procedure and is capable of resolving higher-mode dispersion curves. The credibility of the first higher-mode dispersion curve shown in Figure 3 is especially essential because it is more sensitive than the fundamental mode to the depth of the layer interface and the surface layer $S$ wave velocity (Figure 4) and consequently has more influence on the grid search results (Figure 5).

[15] The $P$ wave seismogram profiles used in generating the frequency-phase velocity image are the same as those used in the refraction analysis (Figure 2) and the time domain Rayleigh wave phase picks (Figure 3). The transformed frequency-phase velocity images are compared with the dispersion curves in Figure 3 and are plotted in Figure 8. Figure 8a was generated by discarding the first seven geophones out of the total 24 geophones of the linear array. In general, the fundamental mode surface wave trains are not clearly shown and well developed in the receiver distance shorter than the seventh geophone. Results of the time domain and frequency-wave number spectral methods are consistent. Although the frequency-phase velocity image has a wider power ratio range within the 0.90 amplitude ratio at lower frequency ($<\sim 10$ Hz) than that at higher frequency, both methods again consistently resolve the fundamental mode dispersion. The wider power ratio range shown at low frequency might be due to the relatively long wavelength (30 m for a 10 Hz wave traveling at a velocity of 300 m/s) compared to the source-receiver distance (longest at 48 m) and time sampling problems for the short record length of 512 ms. In contrast, wavelengths associated with the first higher-mode dispersion curve (>37 Hz) are shorter than 10 m.

[16] The resulting $V_p$ and $V_s$ of the surface layer and the surface layer thickness interpreted from two different dispersion data sets are closely comparable. The best jointly modeled Earth model for the array site is summarized in Table 1. The $V_p$ and $V_s$ of the surface layer interpreted from the hammer-generated Rayleigh wave dispersion appears to be better resolved on the basis of the distribution of the minimum mean 1-norm residuals than that from the air-coupled Rayleigh wave dispersion. This difference might be attributed to the different frequency coverage between the two dispersions where the higher-frequency hammer-generated Rayleigh wave dispersion is more sensitive to the surface layer $V_p$ and $V_s$ than the lower-frequency air-coupled Rayleigh wave dispersion. The surface layer thickness can be bounded by a lower limit at a thickness about 10 m by the air-coupled Rayleigh wave dispersion grid search plots (Figure 6). However, such a lower limit is not explicitly defined in the hammer-generated Rayleigh wave dispersion grid search plots (Figure 5) suggesting again the different frequency sampling converges between the two dispersions.

[17] The theoretical Rayleigh wave dispersion based on the refined Earth model is plotted in Figure 9 against the observed air-coupled (Figure 9a) and hammer-generated (Figure 9b) Rayleigh wave dispersion. Figure 9 shows that these two theoretical Rayleigh wave dispersions both match well with the observed dispersions. We also compared the observed air-coupled Rayleigh wave dispersion from

![Figure 7](image)

**Figure 7.** Contour plot of mean 1-norm phase velocity residuals of the air-coupled Rayleigh wave dispersion curve fits. The surface layer $V_p$ and $V_s$ are chosen as 425 and 300 m/s, respectively, and the layer thickness as 11.5 m. Grid interval of 10 m/s in seismic velocities was used. The seismic velocities shown in the title are the best fit ranges of the lower half-space $V_p$ and $V_s$. The dashed line shows zero Poisson's ratio. Residuals with Poisson’s ratio larger than −0.25 are shown.
thunder and the theoretical high-frequency Rayleigh wave fundamental mode dispersion in Figure 9b. Interestingly, the resulting comparison shows that the observed air-coupled Rayleigh wave dispersion is closely related to the theoretical standard Rayleigh wave dispersion. However, it should not match perfectly since the standard Rayleigh wave dispersion calculation does not use the same or correct boundary condition at the top surface regarding the air-coupled ground motion (i.e., fluid-solid boundary). The effect of the fluid-solid boundary might be subsumed in the variances in the solid material parameters. Further study is needed to quantify the difference between two boundary conditions.

There is one event, event 16, that is the only event with nearly vertical incidence observed in paper 1 showing short-duration impulsive ground motion waveforms and suggesting that most seismic energy penetrated into the substrate. The constrained lower half-space $V_p$ in this paper is at about 950 to 970 m/s, which is slower than the incident wave horizontal phase velocity of about 1.35 km/s, hence producing no significant reverberations. Additionally, the main phases or arrivals of the impulsive acoustic-to-vertical ground motion transfer functions of event 16 with nearly vertical incidence provide additional constraints on the site structure. The observed and synthetic pressure and seismic
waveforms and their corresponding acoustic-to-vertical ground motion transfer functions of event 16 are plotted and compared in Figure 10. As shown in Figure 10, the two transfer functions are generally comparable to each other. The time difference between the directed $P$ ($P$) and the reflected $P$ ($Pp$) shown in Figure 10 is simply calculated by assuming the $Vp$ and thickness of the surface layer are 425 m/s and 11 m (Table 1), respectively. The timing of the reflected $P$ ($Pp$) closely matches the peaks in both the observed and synthetic transfer functions and, is consistent with the $Vp$ and thickness values of the surface layer listed in Table 1.

[19] For the acoustic-to-radial ground motion transfer functions observed in paper 1, the initial motions consistently show reverse direction of the wave propagation direction meaning backward radial initial motion. Langston [2004] modeled and suggested that a solid with a Poisson’s ratio less than about 0.25 will, in theory, display the backward radial initial motion for a compressional acoustic wave. Our constrained site structure (Table 1) indeed has a Poisson’s ratio much less than 0.25 for the surface layer.

[20] The smaller the value of Poisson’s ratio, the larger the volume change or the compressibility produced by a given load. A low Poisson’s ratio material (or a high compressibility medium) has very small or even negative extensional strain in the lateral direction for a corresponding compressional pressure. An example of such a material is a kitchen sponge. Unconsolidated sands and peats have near zero to negative Poisson’s ratios as studies by Aracne-Ruddle et al. [1999], Berge and Bertete-Aguirre [1999], and Prasad et al. [2004]. The array site is within the unconsolidated Eocene Memphis Sand formation and our low value of Poisson’s ratio is consistent with these laboratory measurements.

[21] Langston et al. [2005] estimated the $Q_p$ and $Q_s$ as 200 and 100, respectively, for the thick, unconsolidated
seeds of the Mississippi embayment using explosion-generated Rayleigh waves and $P$ waves. Pujol et al. [2002] reported 18–44 for $Q_s$ at three VSP borehole sites to depths of up to 60 m in the Mississippi embayment. In this study the $Q_p$ and $Q_s$ are chosen as 160 and 80 for all the synthetic computations, respectively. There are slight changes in reverberation period with different $Q$ in the synthetics not shown here and these changes in period are smaller than the frequency errors of the dispersion shown in Figure 9a. Thus we expect $Q$ to have insignificant effect on the inferred velocity structure (Table 1).

[22] There is another type of dispersed seismic wave, “leaky” mode $PL$ propagation [Oliver and Major, 1960], that was observed in the sonic boom-induced ground motions by Langston [2004]. We expect that the characteristic frequency of air-coupled “leaky” mode wave may also be used to find near-surface velocity structure. Both “locked” mode Rayleigh wave and “leaky” mode $PL$ wave propagations require low surface $P$ and $S$ wave velocities to effectively couple with the pressure incidence.

[23] The results in our study suggest the possibility of using natural or controlled (e.g., air cushion vibrator [Waters, 1987]) airborne pressure sources to excite the air-coupled seismic wave and from that to extract the seismic wave characteristics that depend on the near-surface site structure. Strong acoustic-to-seismic coupling requires low surface $P$ and $S$ wave velocities. Using a controlled airborne source pressure could provide a wider incident pressure frequency band than natural thunder pressure, which mainly has the maximum spectral amplitude at a frequency below 10 Hz [Bhartendu, 1964; Balachandran, 1979; Holmes et al., 1971; Lin and Langston, 2007].

[24] The technique used to extract of the hammer-generated Rayleigh wave (Figure 3) and the use of a grid search procedure to find the best fit model parameters are specific to the nature of the data and the particular site structure. The main intention in this study is to present a new seismic source, air-shock wave from thunder, for near-surface site characterization and not be greatly emphasized on data processing techniques. Currently it might not be practical to build a seismo-acoustic array for shallow site characterization compared to using near-surface refraction/reflection and surface wave techniques, but this study provides an example of using acoustic-to-seismic coupling to constrain near-surface site structure and might lead to a more portable, effective, and faster near-surface site characterization technique using portable broadband acoustic pressure sources.

6. Conclusions

[25] We used the air-coupled ground motions from thunder observed in paper 1, near-surface refraction, and Rayleigh wave dispersion measurements to constrain the array site structure. The ranges for the site velocity structure parameters were first determined by the near-surface refraction. The two Earth models interpreted from the air-coupled

![Figure 10.](image)
and hammer-generated Rayleigh wave dispersions are comparable with each other. By jointly modeling the two dispersions, the surface layer $V_p$, $V_s$, and thickness are in the ranges of 425 to 435 m/s, 295 to 300 m/s, and 11 m, respectively. The lower half-space $V_p$ and $V_s$ are about 950 to 970 m/s and 650 to 670 m/s, respectively, constrained by the air-coupled Rayleigh wave dispersion alone. The impulsive acoustic-to-vertical ground motion transfer function of event 16 (paper 1) and its reflected $P$ wave time are consistent with that calculated by the resulting Earth model parameters. The low surface layer Poisson’s ratio of the resulting site structure is consistent with the observed backward radial initial ground motion in paper 1.

[26] The impulse response of the ground to incident acoustic pressure can be sufficiently estimated by the acoustic/seismic deconvolution procedure. Thunder-induced ground reverberations caused by the trapped propagating wave in the layer have a clear systematic dispersion relation to the incident wave. Such dispersion is useful to constrain the near-surface velocity structure because ground motion from an acoustic shockwave depends on the near-surface velocity structure.

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